

Modeling and Control of Manufacturing Systems

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From real fab to DEM

Effective process times

Control Framework

Approximation model

Control

Conclusions

Discrete Event Modeling of a real factory

- raw process time t₀ and c₀
- setups *t*_s and *c*_s
- TBF *t*_f and *c*_f, TTR *t*_r and *c*_r
- operator delays
- rework
- ...(!)

From real fab to DEM

Effective process times

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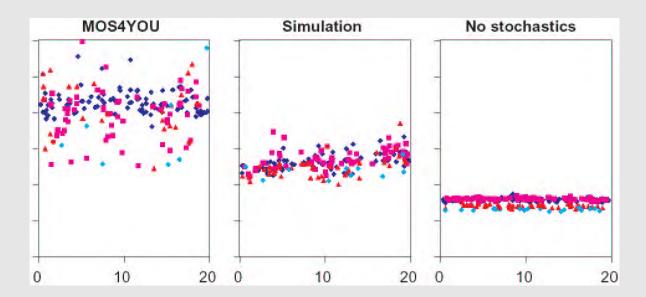
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Results



- smaller mean flow time
- smaller variance flow time

From real fab to DEM

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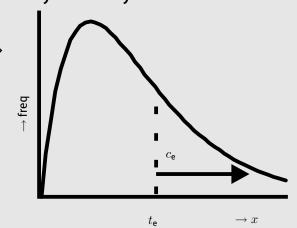
Conclusions

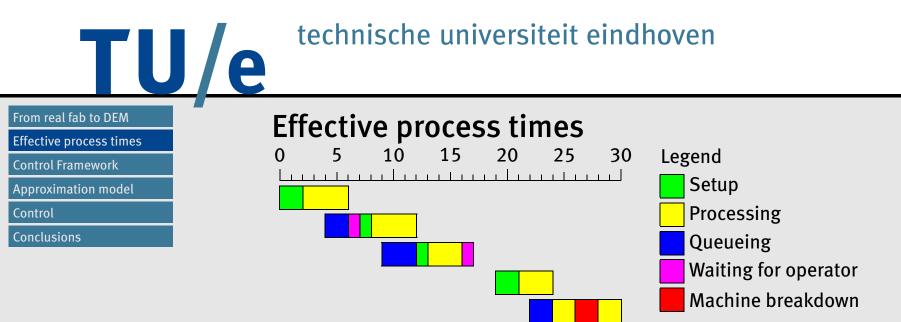
The effective process time method

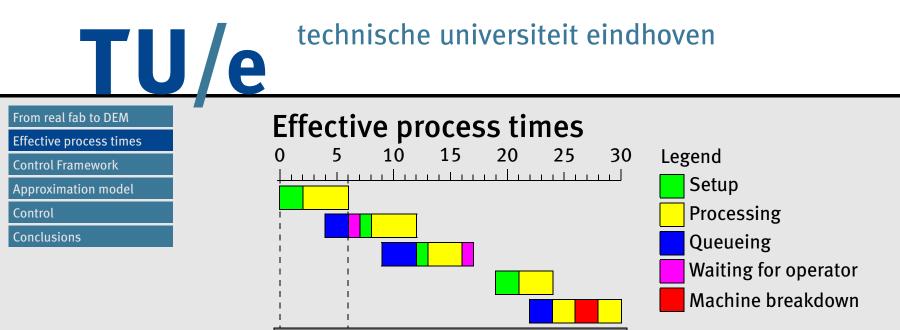
- raw process time t₀ and c₀
- setups t_s and c_s
- TBF t_f and c_f, TTR t_r and c_r
- operator delays
- rework
- ...(!)

Idea:

Combine all disturbances in one single EPT probability density function







EPT 1



From real fab to DEM

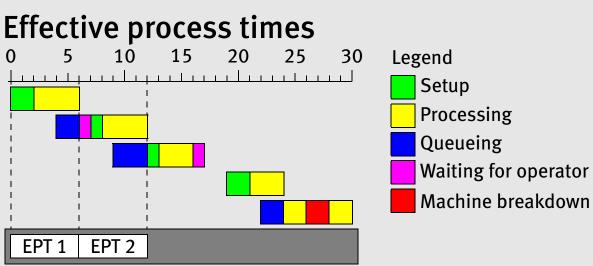
Effective process times

Control Framework

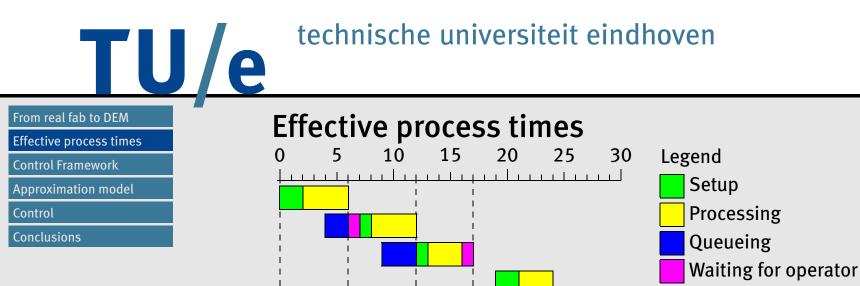
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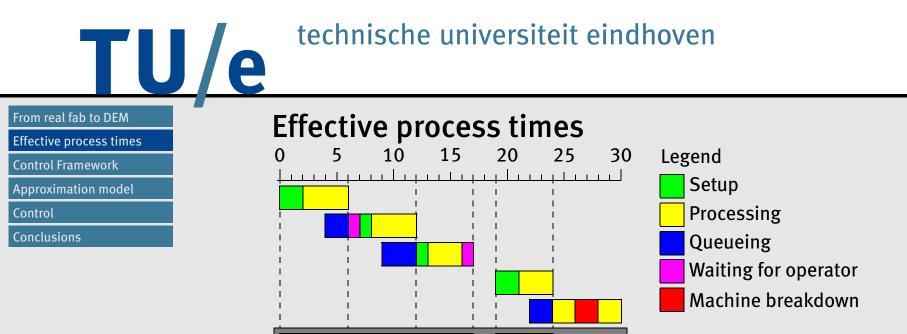




EPT 2 EPT 3

EPT 1

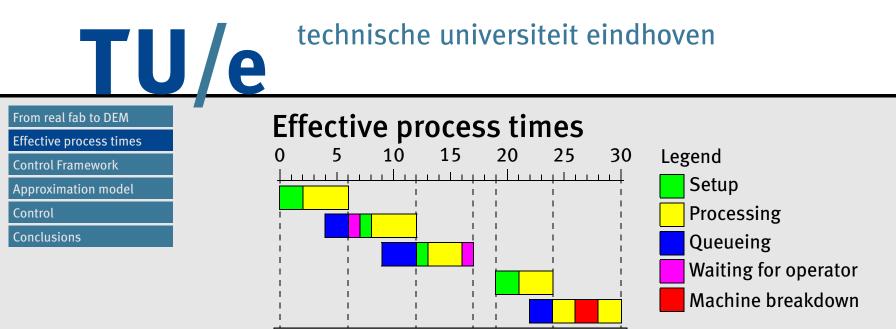
Machine breakdown



EPT 4

EPT 2 EPT 3

EPT 1



EPT 2 EPT 3

EPT 1

EPT 4 EPT 5



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Manufacturing System

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From real fab to DEM

Effective process times

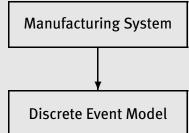
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Effective process times

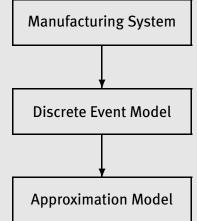
Control Framework

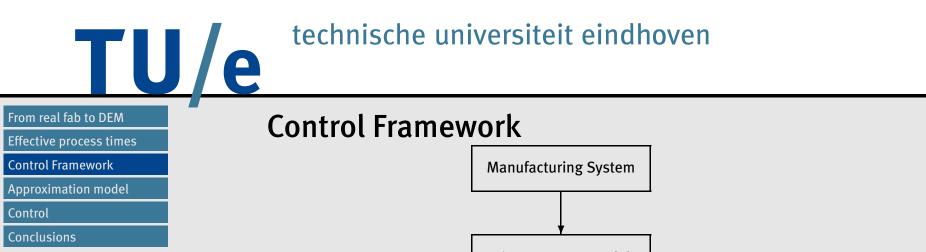
Approximation model

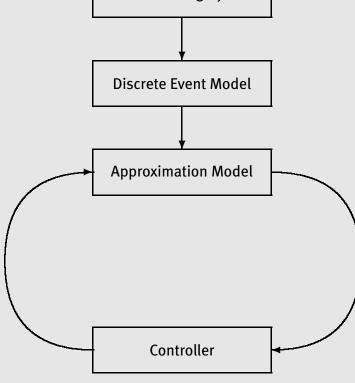
Control

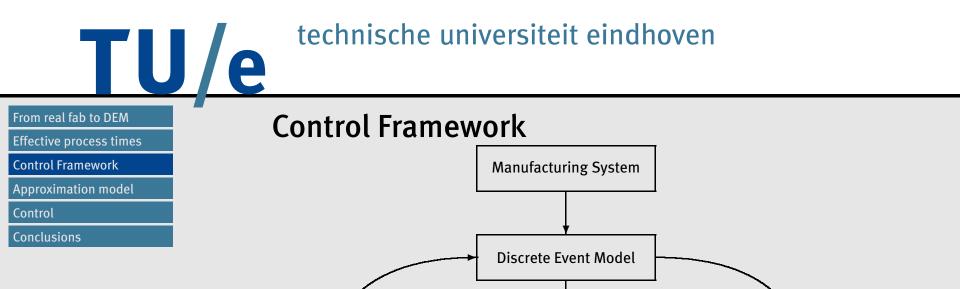
Conclusions





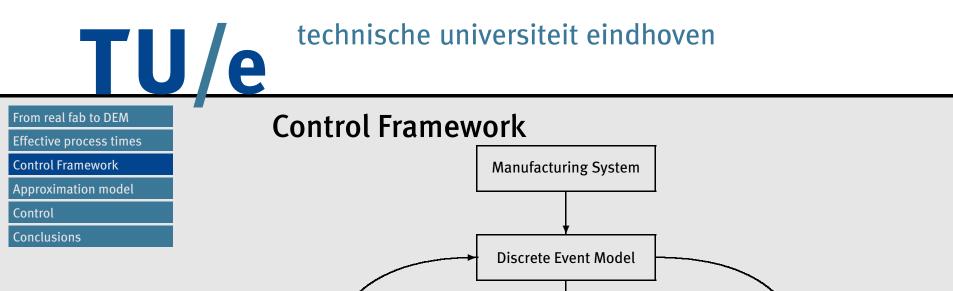






Approximation Model

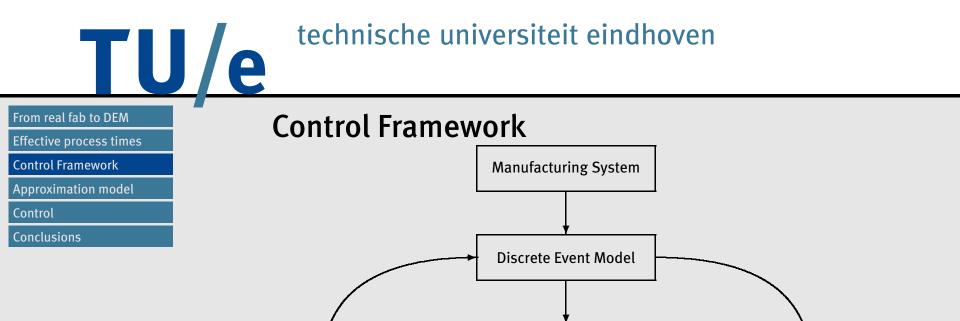
Controller



Approximation Model

Controller





Conversion

Approximation Model

Controller

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Conversion

From real fab to DEM

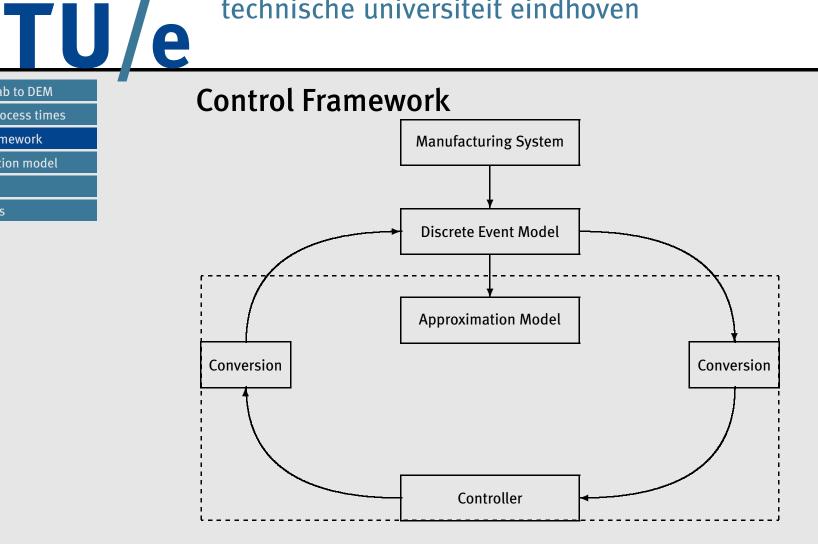
Effective process times

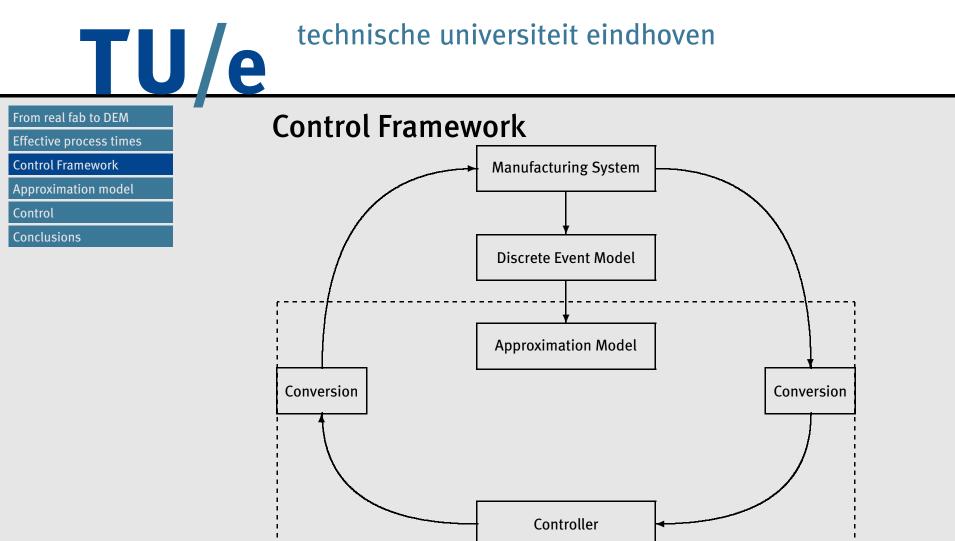
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Approximation model



$$x_1(k+1) = x_1(k) + u_0(k) - u_1(k)$$
$$x_2(k+1) = x_2(k) + u_1(k) - u_2(k)$$
$$x_3(k+1) = x_3(k) + u_2(k) - u_3(k)$$

or

$$\dot{x}_1(t) = u_0(t) - u_1(t) \qquad \dot{x}_1(t) = u_0(t) - u_1(t)$$

$$\dot{x}_2(t) = u_1(t) - u_2(t) \qquad \text{or} \qquad \dot{x}_2(t) = u_1(t - \tau_1) - u_2(t)$$

$$\dot{x}_3(t) = u_2(t) - u_3(t) \qquad \dot{x}_3(t) = u_2(t - \tau_2) - u_3(t)$$

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Modeling manufacturing flow

- density $\rho(x, t)$,
- speed *v*(*x*, *t*),
- flow $u(x, t) = \rho(x, t)v(x, t)$,
- Conservation of mass: $\frac{\partial \rho}{\partial t}(x, t) + \frac{\partial \rho v}{\partial x}(x, t) = 0.$
- Boundary condition: $u(0, t) = \lambda(t)$

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Modeling manufacturing flow

Armbruster, Marthaler, Ringhofer (2002):

- Single queue: $\frac{1}{v(x,t)} = \frac{1}{\mu} (1 + \int_0^1 \rho(s, t) \, ds)$
- Single queue: $\frac{\partial \rho v}{\partial t}(x, t) + \frac{\partial \rho v^2}{\partial x}(x, t) = 0$

$$\rho v^{2}(0, t) = \frac{\mu \cdot \rho v(0, t)}{1 + \int_{0}^{1} \rho(s, t) \, ds}$$

Re-entrant: $v(x, t) = v_{0} \left(1 - \frac{\int_{0}^{1} \rho(s, t) \, ds}{W_{\text{max}}}\right)$

• Re-entrant:
$$\frac{\partial \rho v}{\partial t}(x, t) + \frac{\partial \rho v^2}{\partial x}(x, t) = 0$$

 $\rho v^2(0, t) = \rho v(0, t) \cdot v_0 \left(1 - \frac{\int_0^1 \rho(s, t) ds}{W_{\text{max}}}\right)$

Lefeber (2003):

• Line of *m* identical queues: $v(x, t) = \frac{\mu}{m + \rho(x, t)}$

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Conclusions

Validation studies

- Line of 15 identical machines
- Infinite queues
- FIFO-policy
- Exponential Effective Processing Times
- Step-response (initially empty, start rate λ)
- Model 1, 2, 5 versus averaged discrete event

Rampup to 50% utilization (averaged discrete event) Rampup to 50% utilization (validation studies)

From real fab to DEM

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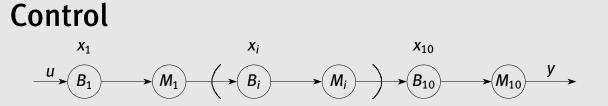
Effective process times

Control Framework

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Control

Conclusions



- Number of machines *n* = 10
- Infinite queues
- FIFO-policy
- Exponential Effective Processing Times
- Mean processing time: 0.5h
- Desired *u* = 0.75 (1.5 lot per h)
- Initial WIP $x_i(0) = 0$

From real fab to DEM

Effective process times

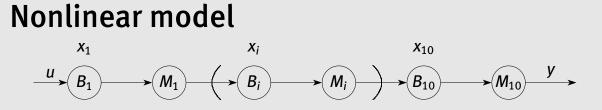
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Control Framework

Approximation model

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Conclusions



Discretizing PDE-model yields:

:

$$x_1(k+1) = x_1(k) - \frac{\mu x_1(k)}{10 + x_1(k)} + u(k)$$
$$x_2(k+1) = x_2(k) - \frac{\mu x_2(k)}{10 + x_2(k)} + \frac{\mu x_1(k)}{10 + x_1(k)}$$

$$\begin{aligned} x_{10}(k+1) &= x_{10}(k) - \frac{\mu x_{10}(k)}{10 + x_{10}(k)} + \frac{\mu x_{9}(k)}{10 + x_{9}(k)} \\ y(k) &= \frac{\mu x_{10}(k)}{10 + x_{10}(k)} \end{aligned}$$



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MPC controller design

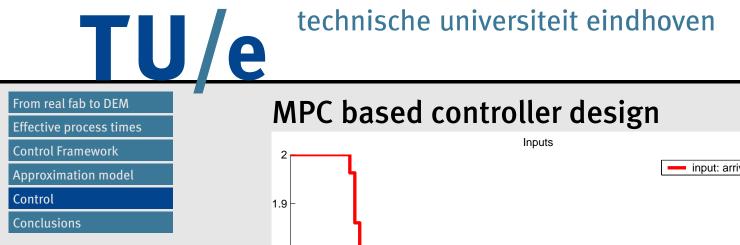
- Prediction horizon *p* = 100h
- Control horizon p = 5h
- Control constant over periods of 1h
- Time sampling: 40 steps per 1h

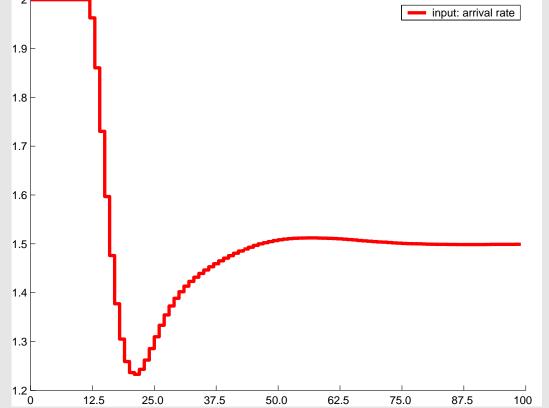
Cost function:

$$\min_{u} \sum_{i=0}^{p} ||y(k+i|k) - y_{des}||_{Q}^{2}$$

Constraints:

$$0 \leq u(k) \leq 2 \qquad 0 \leq \frac{\mu x_i(k)}{1 + x_i(k)} \leq 2$$





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Conclusions

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• EPT can be used to get from real data to simple queue-

ing network model

- Control framework
- Control example

